Brain Signal Acquisition

Course S2022

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Background

- The brain communicates using spikes-- produced when the neuron receives enough input current from other neurons via synaptic connections.

- Recording brain activity are based on detecting changes in electrical potentials in neurons
  - invasive techniques based on implanting electrodes

- Or on detecting changes in large populations of neurons
  - noninvasive techniques such as electroencephalography or EEG

Recording signals from brain

Invasive Approaches:

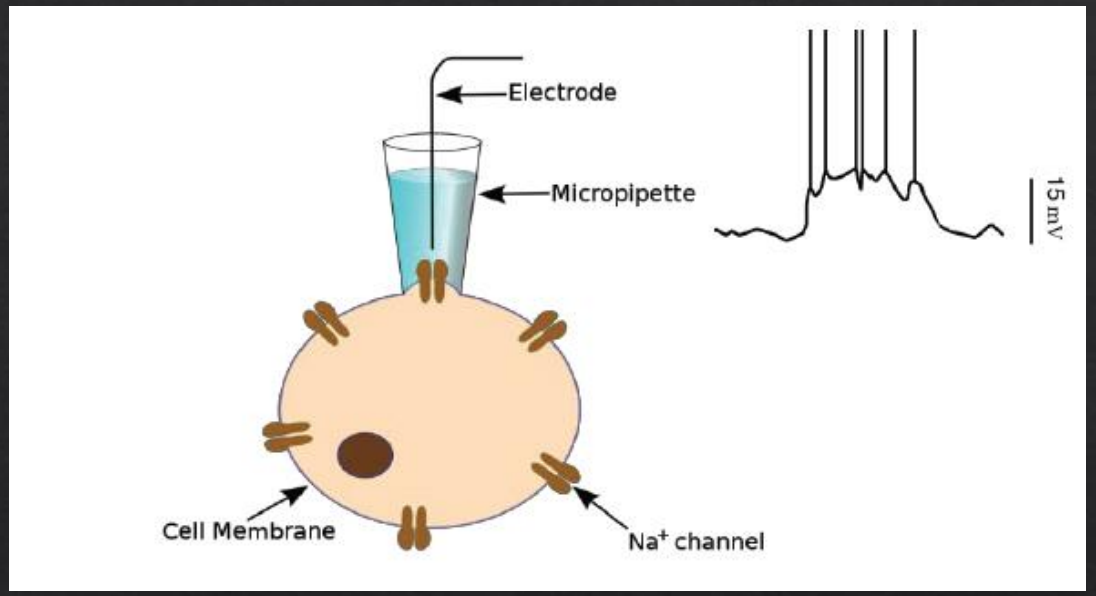
- Techniques that allow recording from individual neurons in the brain are typically invasive.
- They involve some form of surgery,
  - A part of the skull is removed, an electrode or implant placed in the brain, and the removed part of the skull then replaced.
- A major advantage of invasive recordings is that they allow recording of action potentials at the millisecond timescale.

Invasive Approaches

- **Microelectrodes:**
- A *microelectrode* is simply a very fine wire or other electrical conductor used to make contact with brain tissue.
- A typical electrode is made of tungsten or platinum- iridium alloy and is insulated except at the tip, which measures around 1μm in diameter (A neuron's cell body diameter is in the range of tens of μm).

Invasive Approaches

- **<u>Intracellular Recording:</u>**
- Measures the voltage or current across the membrane of the neuron.
- The most common technique, known as *patch clamp recording.*

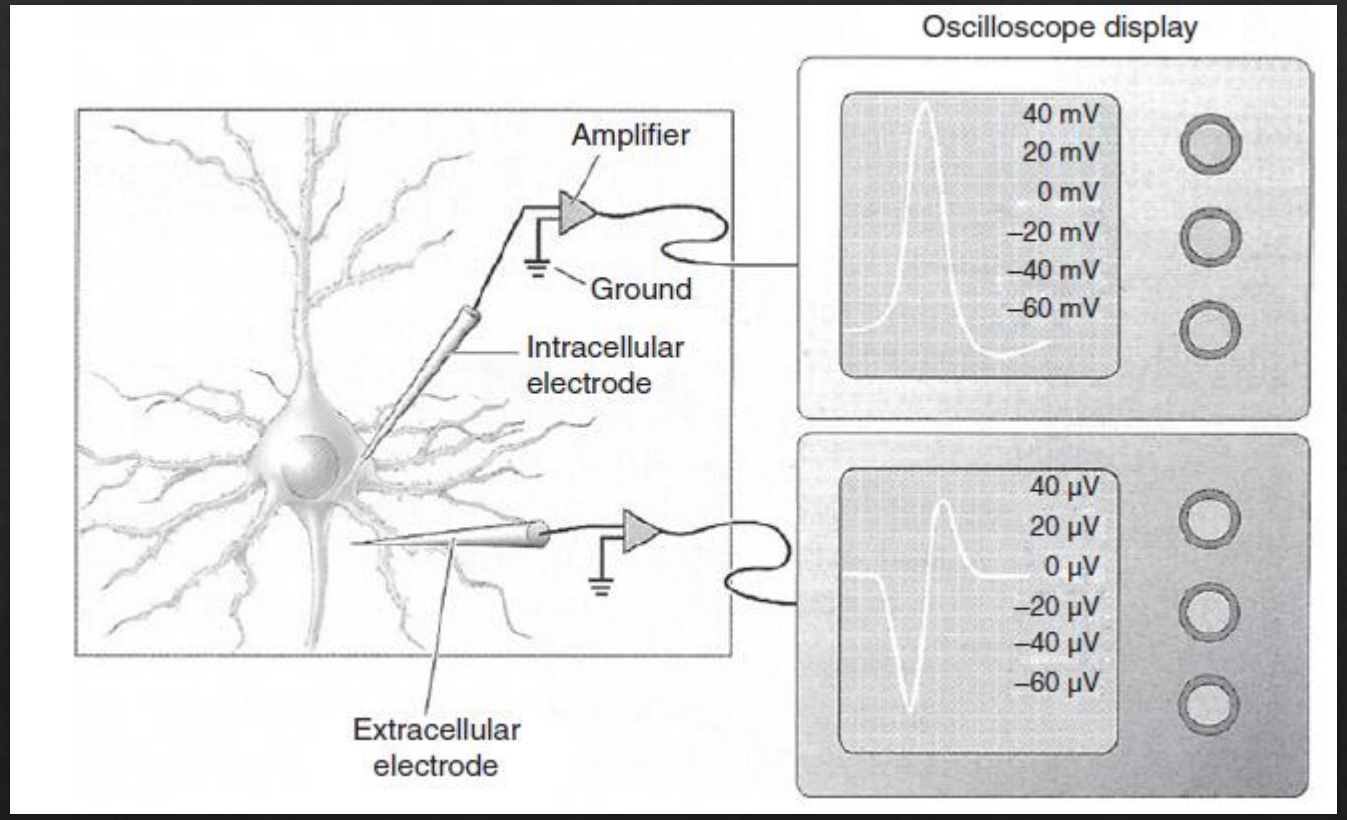


- Very Delicate → Intracellular recordings are typically performed only on slices of brain tissue

Invasive Approaches

- **Extracellular Recording:**
- Recording of a single neuron (or single“unit”): a tungsten or platinum-iridium microelectrode with a tip size of less than 10 microns is inserted into the target brain area.
- The magnitude of the recorded signal is usually less than a millivolt and thus requires the use of amplifiers to detect the signal.
- The signal from the amplifier is fed to a computer, which performs additional processing such as filtering noise and isolating the spikes (action potentials).

Invasive Approaches



(from Bear et al., 2007).

Invasive Approaches

- When the neuron produces a spike, positive ions flow away from the extracellular electrode into the neuron, causing the initial negative deflection in the display. This is followed by a positive deflection as the action potential decreases and positive charges flow out of the neuron toward the extracellular electrode.

Invasive Approaches

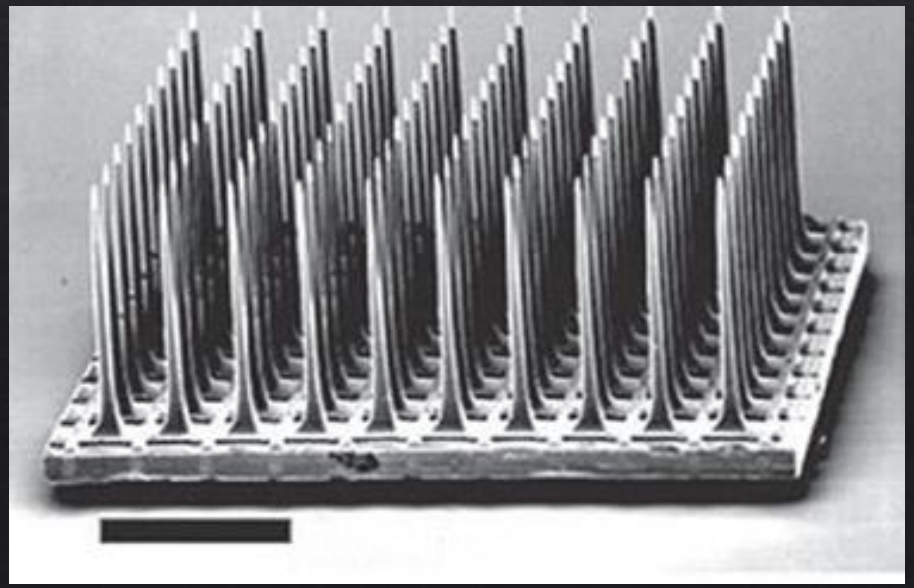
Tetrodes and Multi-Unit Recording:

- To record from multiple neurons simultaneously by using more than one electrode.
- Four wires are tightly wound together in a bundle.

Invasive Approaches

Multielectrode Arrays:

- To record from larger numbers of neurons, microelectrodes can be arranged in a grid-like structure to form a multielectrode array of $m \times n$ electrodes.



(adapted from Hochberg et al., 2006).

Invasive Approaches

- The most common types of implantable arrays are microwire, silicon-based, and flexible microelectrode arrays
- Increased spatial resolution
- The ability to record simultaneously from several dozens of neurons
- Opens the door to extracting complex types of information such as position or velocity signals that could be useful for controlling prosthetic devices.

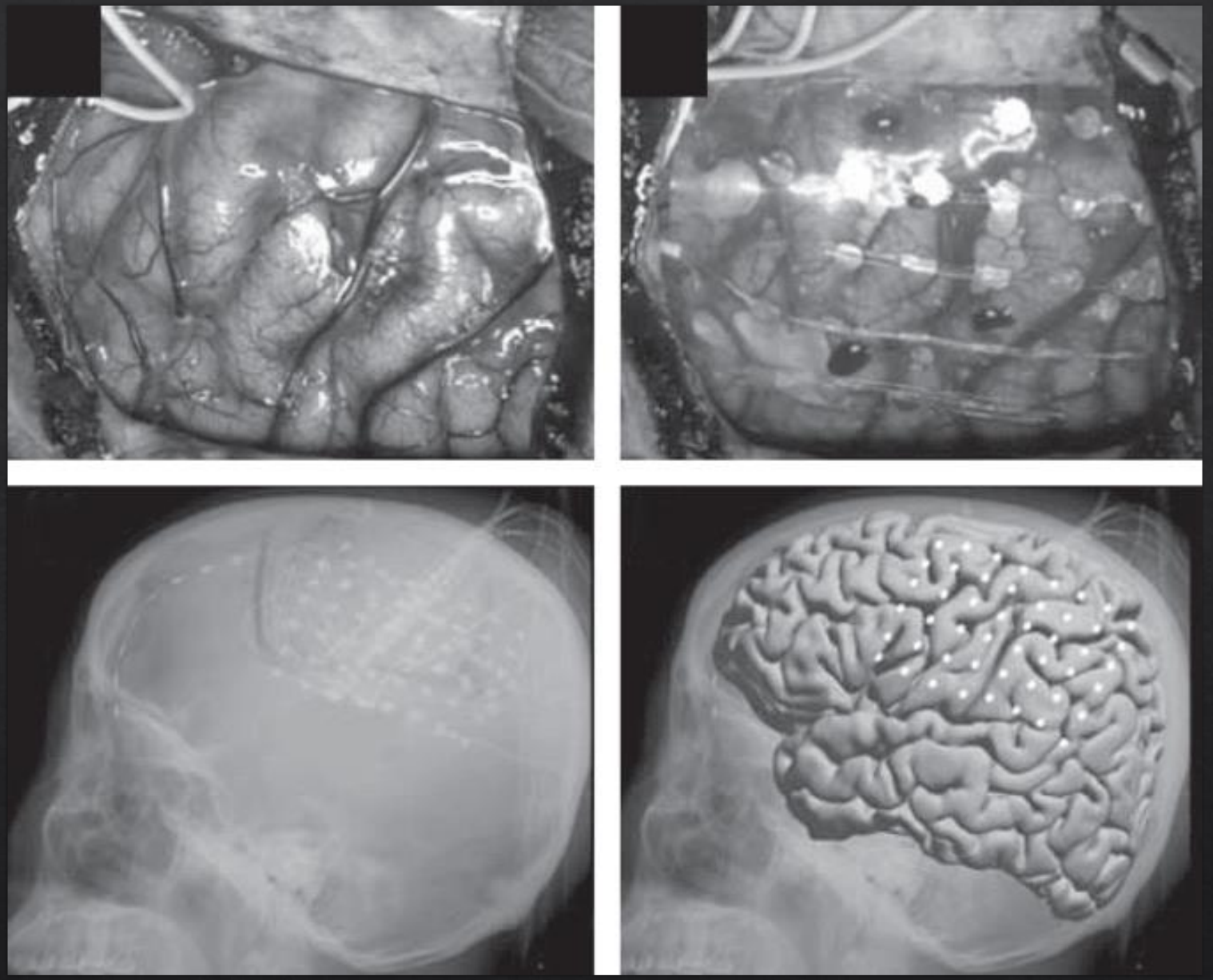
Partially Invasive Approach

Electrocorticography (ECoG):

- *Electrocorticography* (ECoG) is a technique for recording brain signals that involves placing electrodes on the surface of the brain.
- The procedure requires making a surgical incision into the skull to implant the electrodes on the brain surface

Partially Invasive Approach

- ECoG electrodes can record the electrical fluctuations caused by the coherent activity of large populations of neurons (several tens of thousands).
- Safer than arrays implanted inside the brain.
- ECoG electrodes may also be less likely to wear out compared to brain penetrating electrodes
- ECoG offers greater spatial resolution



(from (Miller et al., 2007).

Partially Invasive Approach

MicroECoG:

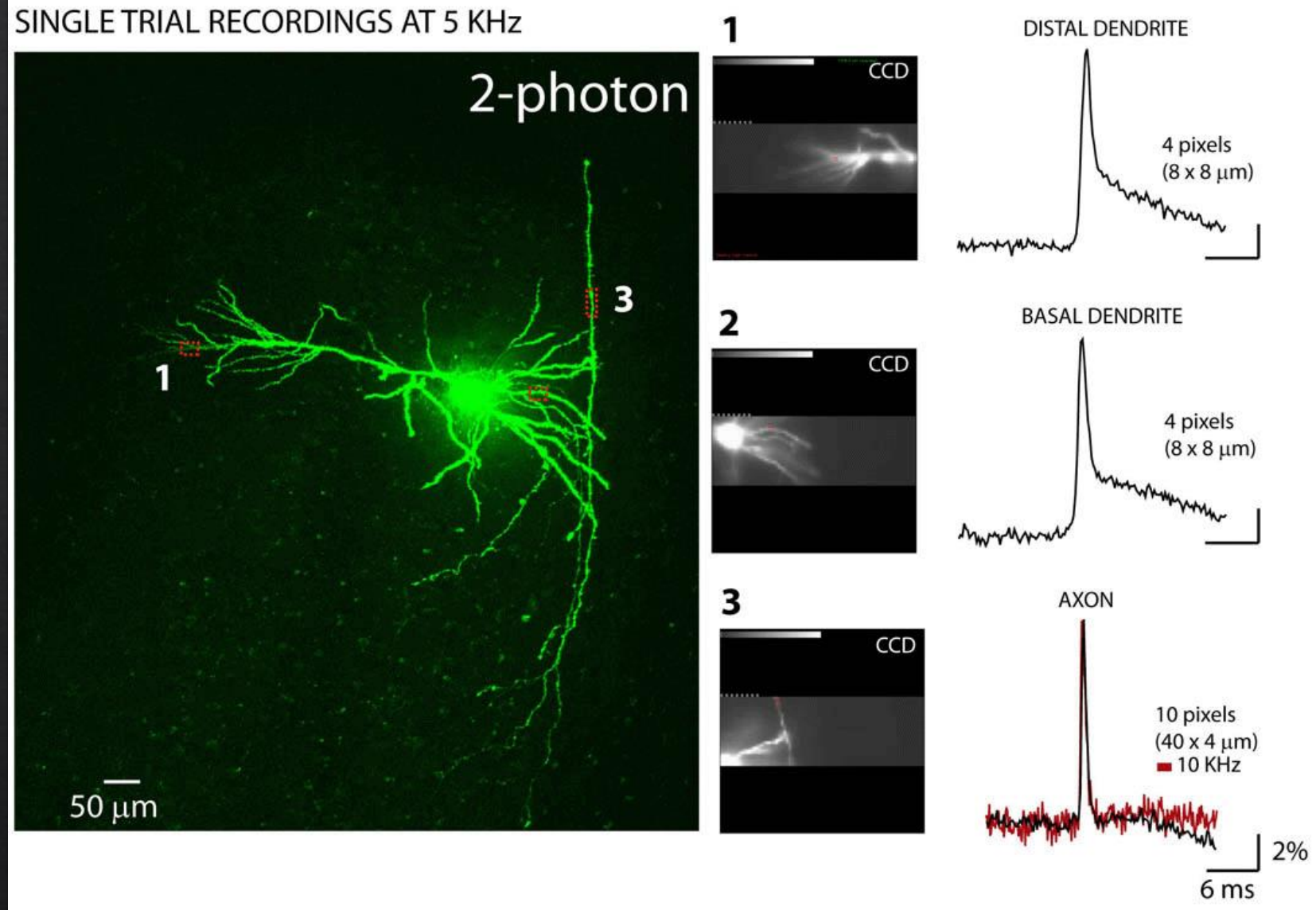
- One disadvantage of ECoG, is the relatively large size of ECoG electrodes
- These microelectrodes are only a fraction of a millimeter in diameter and spaced only 2–3 mm apart in a grid
- Allows detection of neural activity at a much finer resolution than traditional ECoG.
- Decoding fine movements, such as the movements of individual fingers, or even speech, without actually penetrating the brain.

Partially Invasive Approach

Optical Recording: Voltage-Sensitive Dyes and Two-Photon Calcium Imaging:

- Voltage-sensitive dyes
- Neurons are stained with a voltage-sensitive dye
- Dye responds to changes in membrane potential by changing its absorption and/or fluorescence
- Recorded optical signals correspond to summed responses from several simultaneously active neurons.
- Useful for imaging macroscopic features of the brain such as feature maps in the cortex

VOLTAGE-SENSITIVE DYE IMAGING



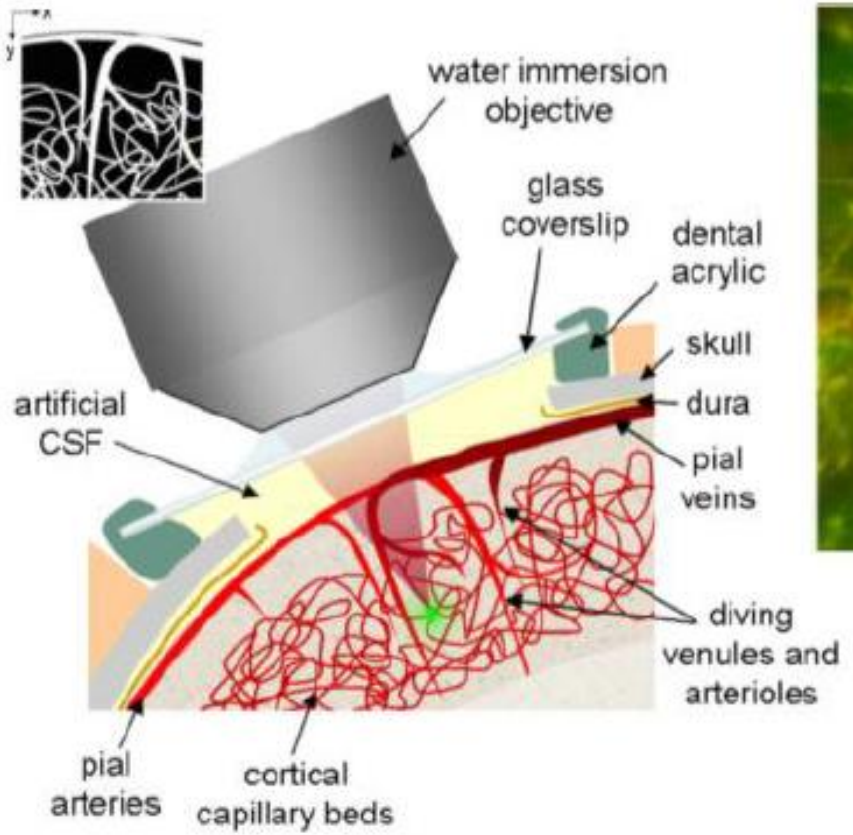
(image: Scholarpedia http://www.scholarpedia.org/article/Voltage-sensitive_dye).

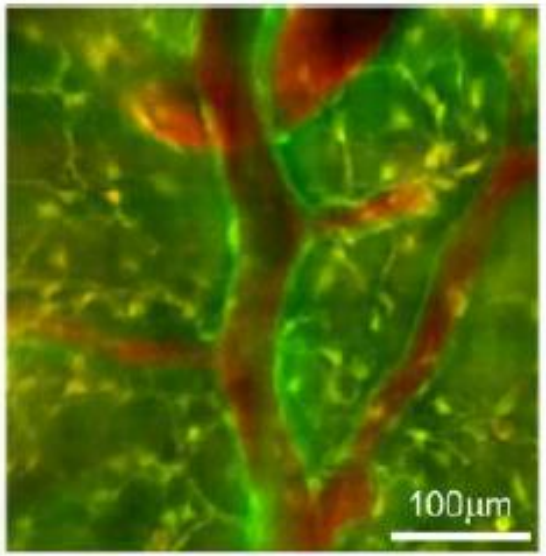
Partially Invasive Approach

- Two-photon calcium imaging
- Based on the fact that electrical activity in neurons is typically associated with changes in calcium concentration.
- Photon calcium imaging involves:

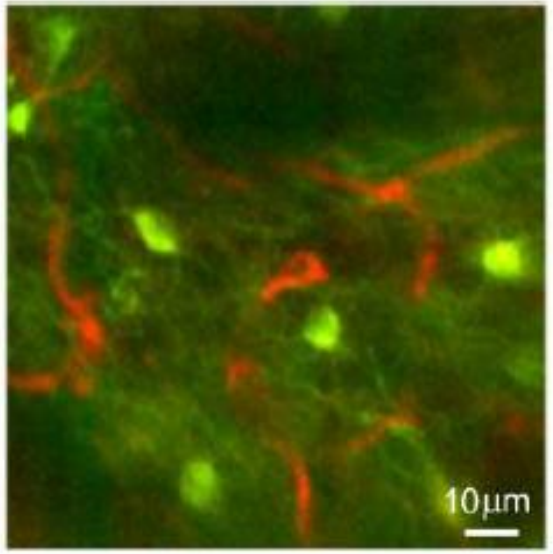
  (1) using pressure ejection to load neurons with fluorescent calcium-indicator dyes

  (2) monitoring changes in calcium fluorescence during neural activity using two-photon microscopy.





Oregon Green calcium sensitive dye stained neurons



Transgenic mouse expressing green fluorescent protein (GFP) in a subpopulation of neurons

Image from Kherlopian et al., 2008).

Non Invasive Approaches

Electroencephalography (EEG)

- EEG signals reflect the summation of postsynaptic potentials from many thousands of neurons that are oriented radially to the scalp.
- EEG predominantly captures electrical activity in the cerebral cortex, whose columnar arrangement of neurons and proximity to the skull favor recording by EEG.

Non Invasive Approaches

- Electroencephalography (EEG)
- The spatial resolution is typically poor (in the square centimeter range)
  - Due to lots of muscles between the source of signal and the electrodes placed on the scalp.
- The temporal resolution is good (in the milliseconds range)

Non Invasive Approaches

- The measured signals are in the range of a few tens of microvolts, necessitating the use of powerful amplifiers and signal processing to amplify the signal and filter out noise.
- Artifacts in the EEG signal
  - eye movements, eye blinks, eyebrow movements, talking, chewing, and head movements

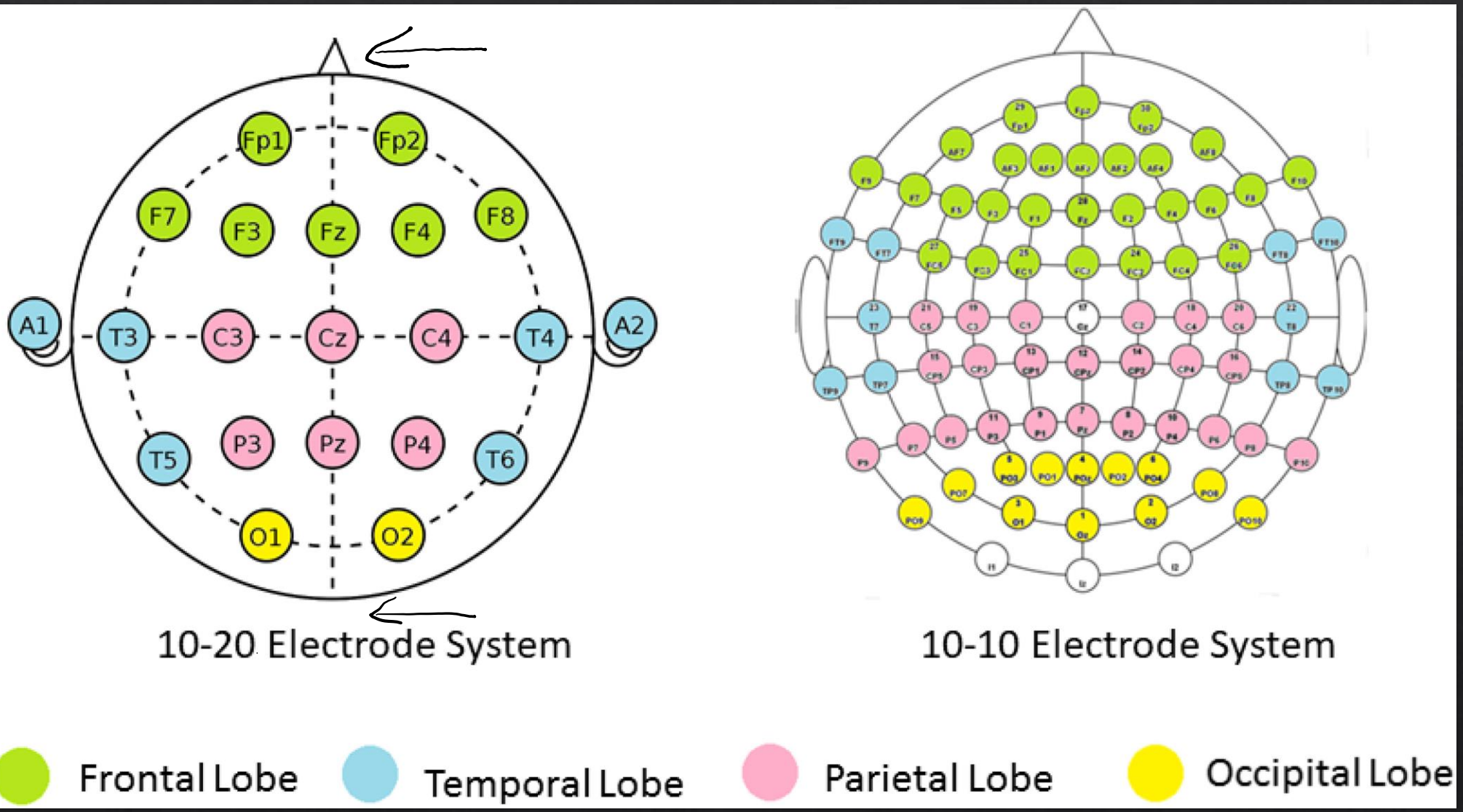
Non Invasive Approaches

- EEG recording involves the subject wearing a cap or a net into which the recording electrodes are placed
- A conductive gel or paste is injected into the holes of the cap before placing the electrodes.

courtesy K. Miller

Non Invasive Approaches

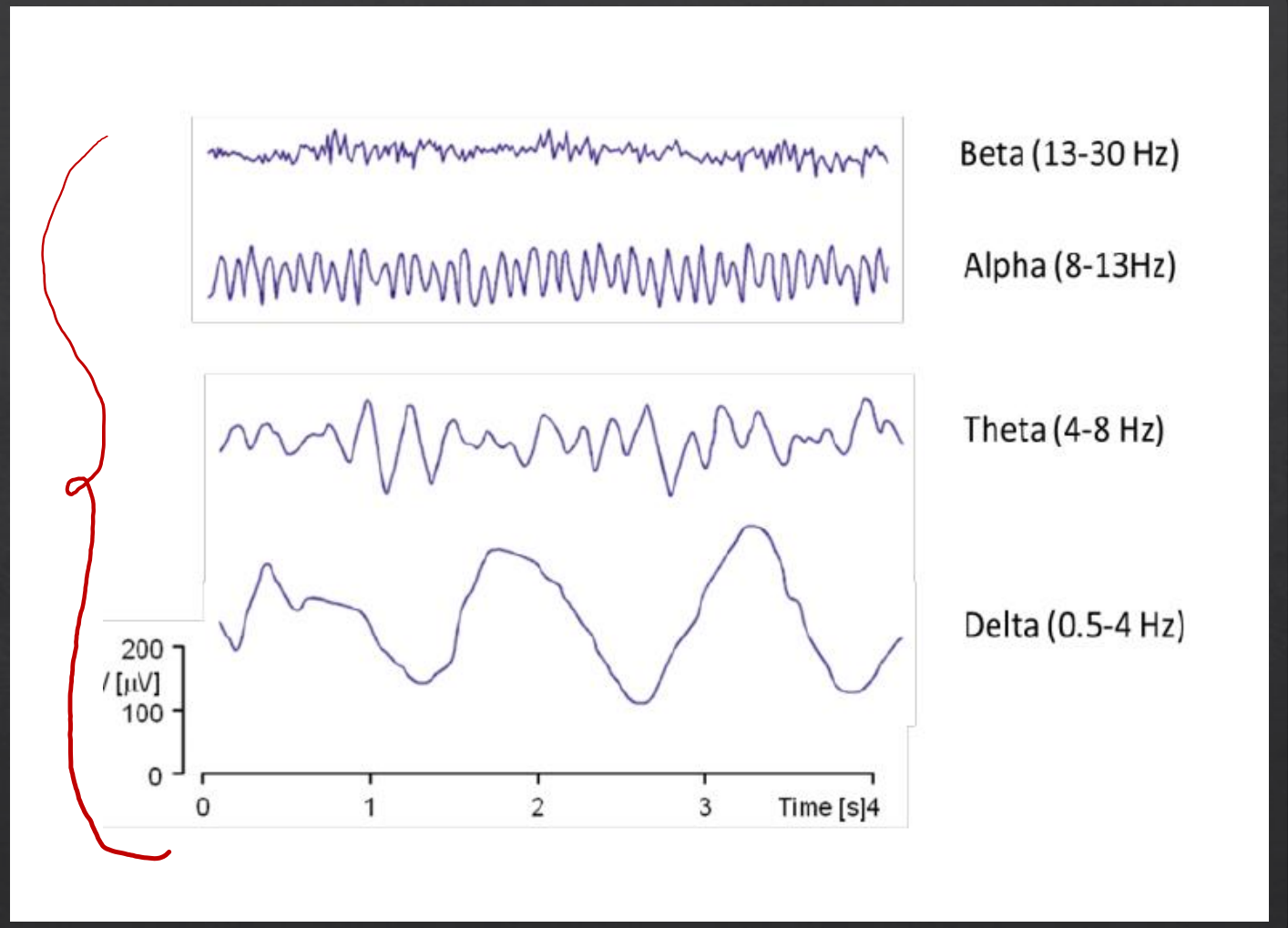
- The international 10–20 system is a convention used to specify standardized electrode locations on the scalp.
- C = central, P = parietal, T = temporal, F = frontal, Fp = frontal polar, O = occipital, A = mastoids


Fp1
Fp2
F7
F3
Fz
F4
F8
A1
T3
C3
Cz
C4
T4
A2
T5
P3
Pz
P4
T6
O1
O2
10-20 Electrode System
10-10 Electrode System
Frontal Lobe
Temporal Lobe
Parietal Lobe
Occipital Lobe

- The mastoids reference electrode locations behind each ear (A1 and A2).
- Other reference electrode locations are nasion, at the top of the nose, level with the eyes; and inion, at the base of the skull on the midline at the back of the head.
- In a typical setup, each EEG electrode is connected to one input of a differential amplifier, and the other input is connected to a reference electrode

- The amplification of voltage between the active electrode and the reference is typically 1,000–100,000 times.
- The amplified signal is passed through a filter and then digitized via an A/D (analog to digital) converter.
- After digitization, the EEG signal may be additionally filtered by a 1–50 Hz bandpass filter.
  - Excludes noise and movement artifacts in the very low and very high frequency ranges.

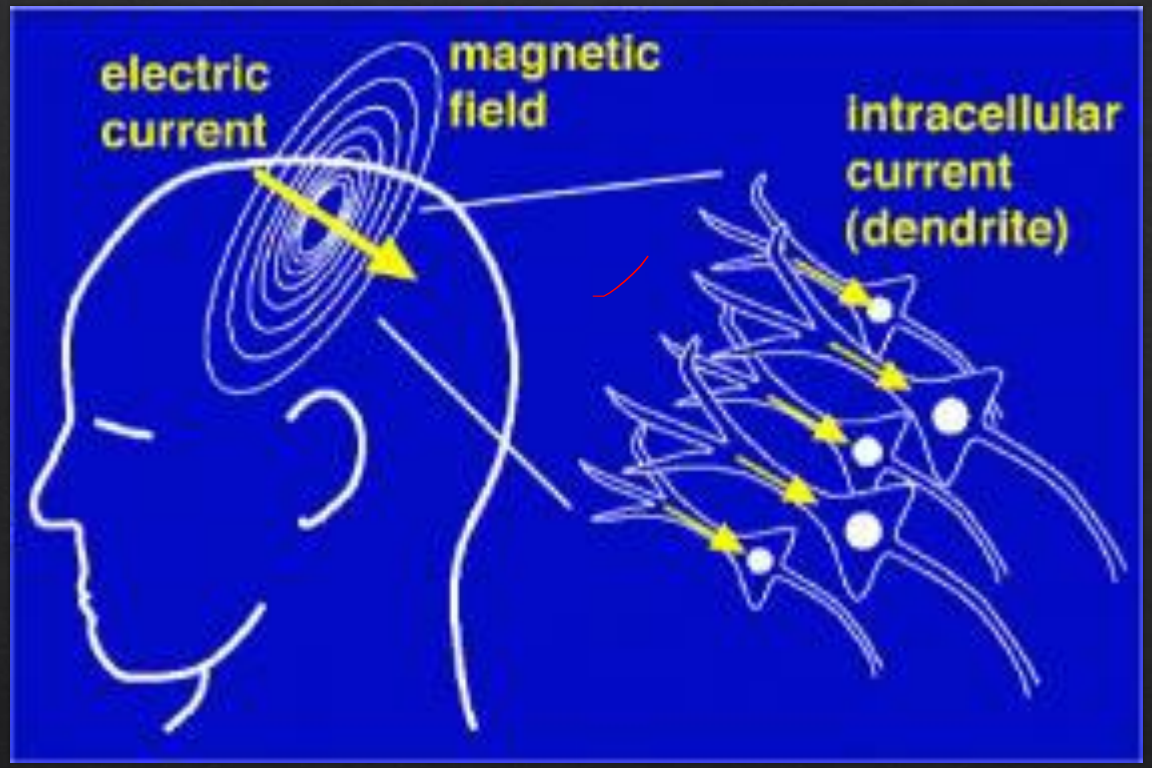
- EEG recordings are well-suited to capturing oscillatory brain activity or "brain waves" at a variety of frequencies
  - Alpha waves (8 to 13 Hz)
  - Beta waves (13 to 30 Hz)
  - Delta waves (0.5-4 Hz)
  - Theta waves (4-8 Hz)
  - Gamma waves (30-100 Hz or more)



Non Invasive Approaches

Magnetoencephalography (MEG):

- Measures magnetic fields produced by activity of thousands of cortical neurons oriented perpendicular to the cortical surface
- Magnetic fields not distorted by skull and scalp
- Better spatial resolution than EEG
- Expensive and bulky
- Magnetically shielded rooms

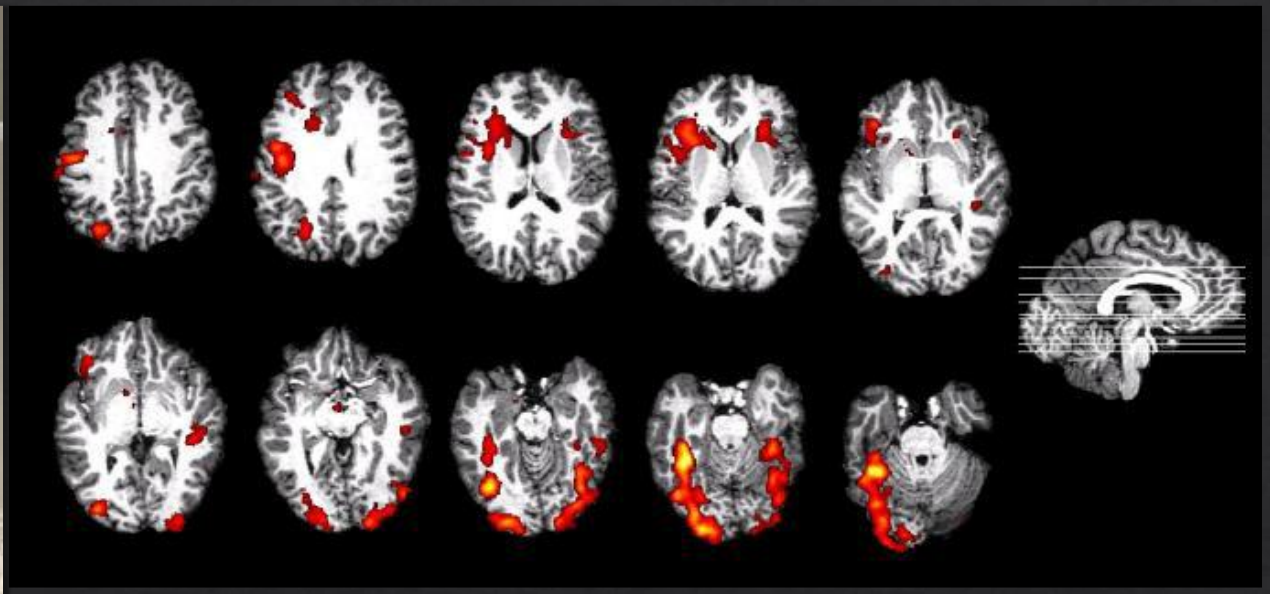


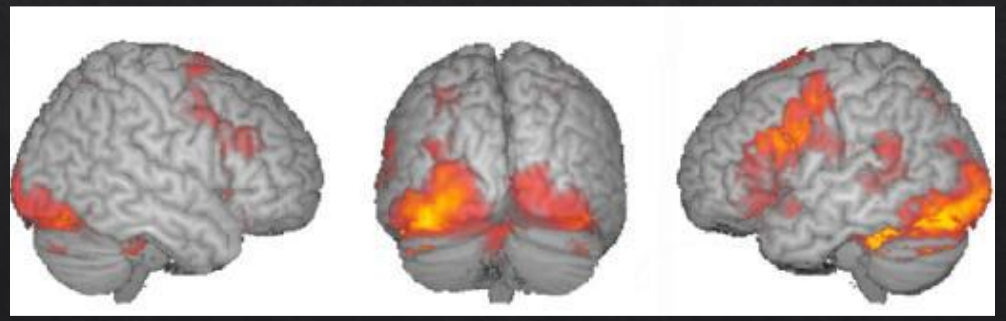
(image A: Wikimedia Commons;
image B: http://dateline.ucdavis.edu/photos_images/dateline_images/040309/DondersMEGOle_W2.jpg).

Non Invasive Approaches

Functional Magnetic Resonance Imaging (fMRI) :

- Measures changes in blood flow due to increased activation of neurons in an area
- Relies on paramagnetic properties of oxygenated and deoxygenated hemoglobin in the blood
- Produces images showing blood-oxygenation-level-dependent signal changes (BOLD)



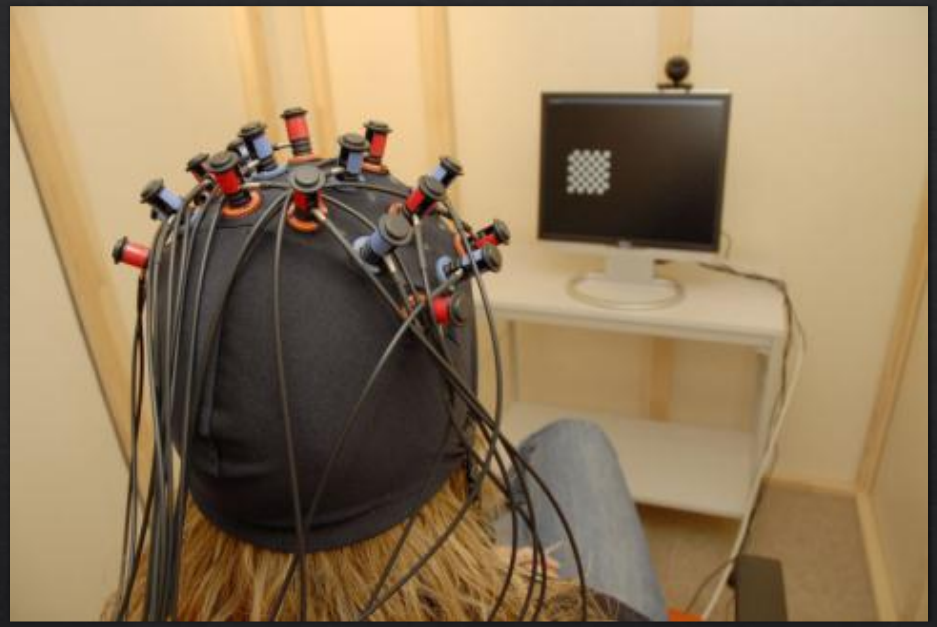


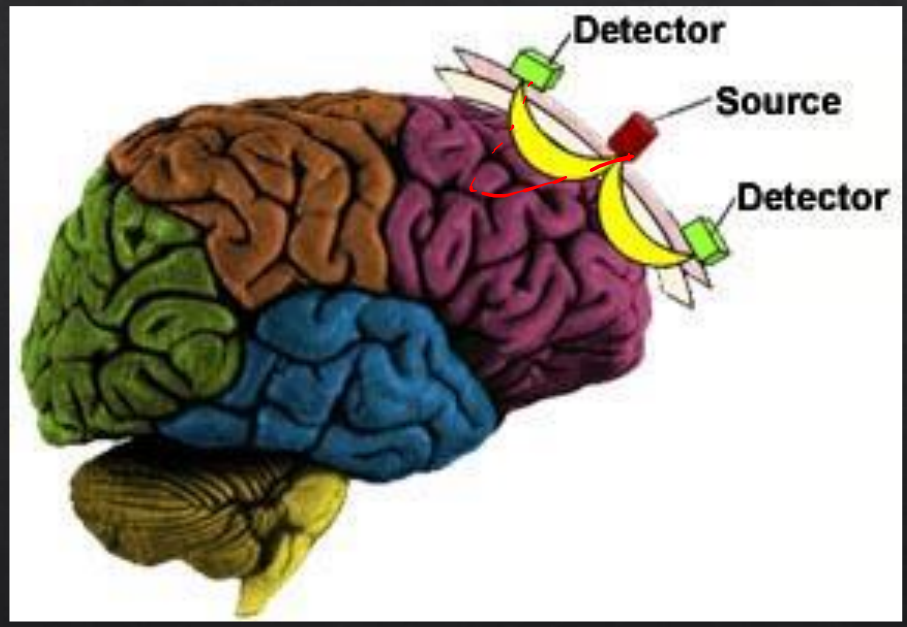
Example fMRI Images (word reading task)

Non Invasive Approaches

Functional Near-Infrared Spectroscopy (fNIR)

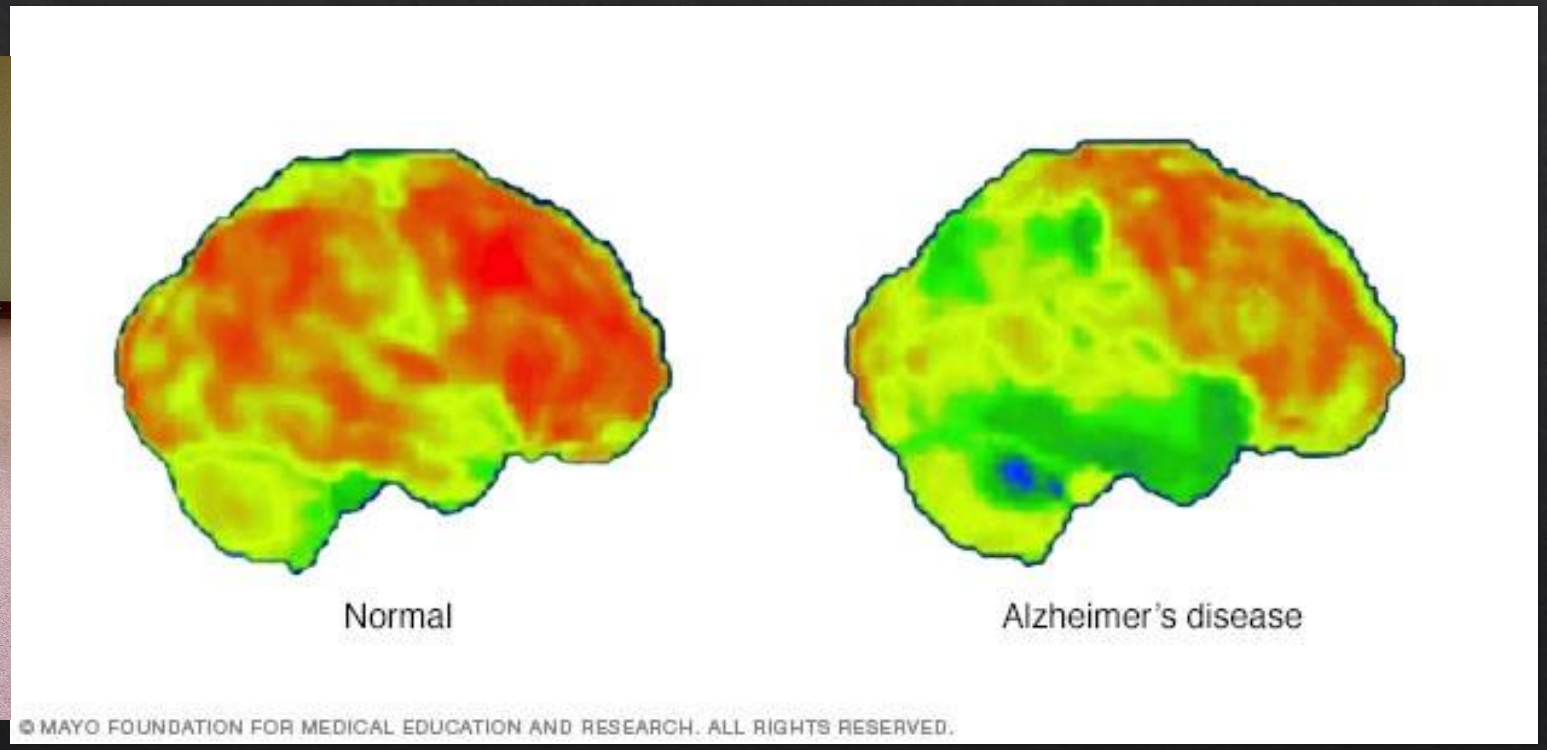
- Measures change in blood oxygenation level caused by increased neural activity in the brain.
- Based on detecting near-infrared light absorbance of hemoglobin in the blood with and without oxygen.
- Maps neural activity using "*optodes*" (emitters and detectors)




Detector
Source
Detector

Non-Invasive Approaches

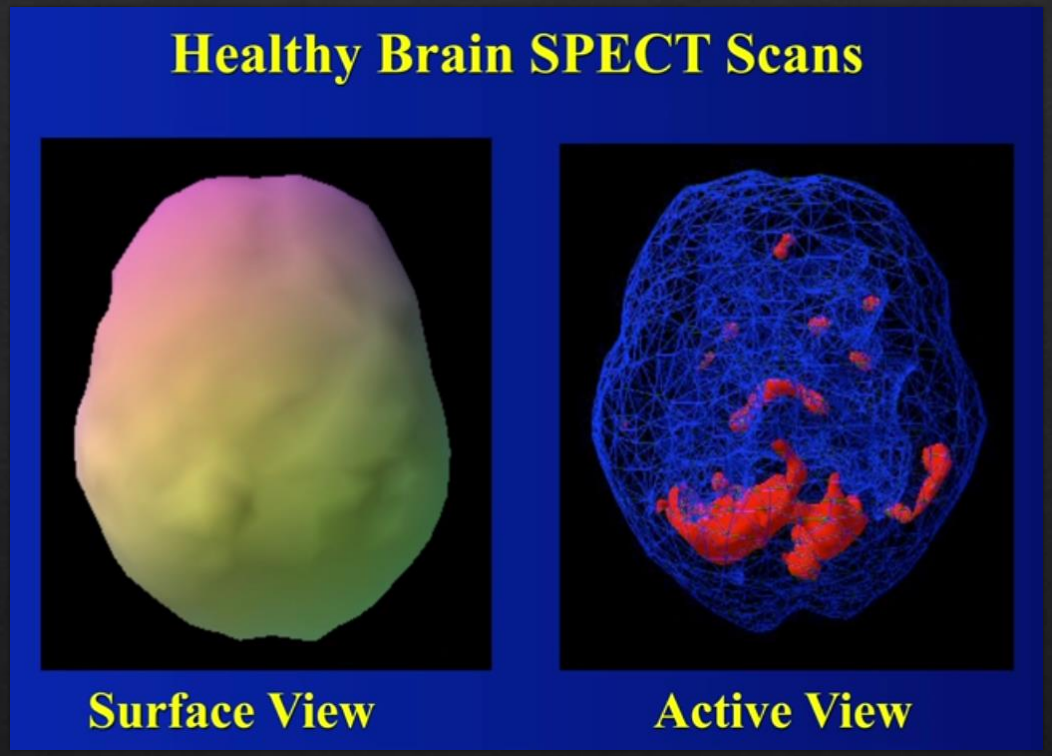
- **Positron Emission Tomography (PET):**
- Measures emissions from radioactively labeled, metabolically active chemicals that have been injected into the bloodstream for transportation to the brain.
  - The labeled compound is called a *radiotracer*.
- Sensors in the PET scanner detect the radioactive compound
  - As a result of metabolic activity caused by brain activity.
- Generate two-or three-dimensional images indicating the amount of brain activity.



A PET scan can compare a normal brain (left) with one affected by Alzheimer's disease (right). An increase in blue and green colors shows decreased brain metabolic activity due to Alzheimer's disease.

Non Invasive Approaches

- Single-photon emission-computed tomography (**SPECT**):
- SPECT is a nuclear medicine technique that uses gamma rays to study the brain.
- A radioactive substance is injected into the patient's body and is scanned using a SPECT machine.
- Allows doctors to see how blood flows into tissues and organs.
  - Active, inactive, or overactive.
- Averages the brain activity over a few minutes and generates an image.



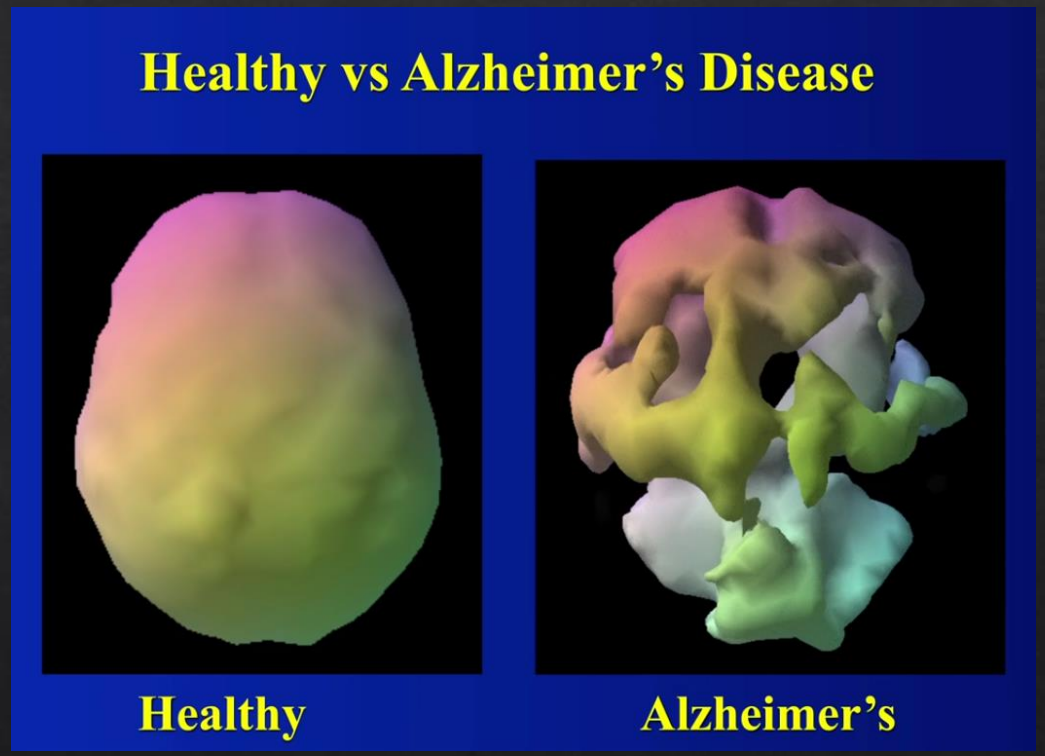


Image credit: https://hamnaqasim.medium.com/brain-scans-a-lesson-to-learn-9dfe67abd841